Evaluation of dam performance under seismic loads with linear time history analysis, case study Grand Ethiopian Renaissance RCC main dam

Alessandro Masciotta
Studio Masciotta
Via E. Q. Visconti, 55
00193, Rome, Italy

Alberto Bezzi
Studio Pietrangeli
Via Cicerone, 28
00193 Rome, Italy

Carlo Fontana
Studio Masciotta
Via E. Q. Visconti, 55
00193, Rome, Italy

Angelo Fiorani
Studio Masciotta
Via E. Q. Visconti, 55
00193, Rome, Italy

Summary

The paper shows a systematic and rational application of a methodology to estimate the behavior of concrete structures under seismic loads, using time-history analysis. This rational approach, proposed by USACE EM 1110-2-6051, can be used to evaluate the safety of new or existing structures and moreover to optimize the cost of the construction during the design phase.

The methodology is based on Demand-Capacity Ratio (DCR), that is defined as the ratio of computed tensile stress to tensile strength of the concrete, and on the Cumulative Inelastic Duration (CID), that refers to the total duration of stress excursions above the tensile strength. Generally tensile stresses should not exceed tensile strength; however, during extreme earthquakes, some short stress excursions above the tensile strength have been considered acceptable because they are related with a low or moderate damage of the structure.

The present paper describes how the above said method has been systematically implemented, through the development of a dedicated calculation code, to analyze the behavior under seismic loads of the Grand Ethiopian Renaissance Dam (GERD), along the Nile River. The dam, currently under construction, has a maximum height of 175 m, it's 1780 m long and it has a global RCC volume of 10.2 Mm^3. It is designed to store 74 Bm^3 of reservoir serving a 6140 MW Power Plant.

Introduction

The prediction of the crack pattern within a dam under strong seismic events is, in general, a complex problem. The complexity derives from the fact that modeling the phenomenon, with accuracy and extending the model to the whole dam, involves the use of Non Linear Analyses, which could take into account the behavior of materials in conditions close to yielding/rupture; this is extremely time consuming and presents relevant difficulties, especially in relation to the step by step updating of the pore pressures, mesh and material characteristics. Besides the interpretation of the results of the analysis is particularly complex being the results themselves strictly linked to the load history. Furthermore, Non Linear Models lack a reliable and extensive validation; this is the reason why Non Linear Analyses are generally performed only during the final verification phase, with the purpose of evaluating the entity of crack along potential identified crack surfaces.

Recognizing the criticalities is a task generally performed by means of Linear Analyses, which provide important information about the zones most likely to damage, that could represent the starting points of potential cracks. From the extent of the surfaces interested by overstress and the number of excursions of stress above the theoretical strength of material, it is possible to infer an assessment, at least qualitative, of the expected damage of the structure under a seismic event.

The DCR-CID method represents a valid compromise between the Non Linear Analyses and the Linear ones; in fact, it starts from the Results of a Linear Analysis and it allows an evaluation not only qualitative, but rather numeric, of the performance of the structure in the Non Linear field and of the expected level of damage.

1. Background

Linear time-history analyses provide a reliable tool to inquire the dam behavior under seismic events and they can be considered a necessary step in the analysis progression. In fact, they represent a significant upgrade with respect to the simplified pseudo static methods of analysis which are usually applied in the preliminary phase of design of a gravity dam. The results of linear time-history analyses are usually presented in the form of maximum stress envelope maps; however this kind of result show peak values that are often not simultaneous and does not give any information about the duration of the cycles of overstress.

K. Hatami [10] proposed a methodology to evaluate the seismic performance of a dam which took into account the time variation of the stress response; Hatami' s approach was based on the integration of the positive values of the maximum principal stress time history. Using these local indices computed in correspondence of finite element control points, he defined a global index which was determined considering their average value weighted by the corresponding areas of influence.

Several alternative performance indices have been proposed in the literature as alternative analysis tools that allow a systematic comparison of the effects of different ground motions as indicated by Hall et al. [11].

Currently, the most reliable and widespread method of assessment of a dam stability under seismic events, using linear time history method, is the DCR (Demand Capacity Ratio) - CID (Cumulative Inelastic Duration) method described in USACE Code "Time-History Dynamic Analysis of Concrete Hydraulic Structures", EM 1110-2-6051, 2003 [6].
According to this method, the seismic performance of a dam can be assessed on the basis of simple stress checks obtained from the linear elastic analysis combined with engineering judgment.
Generally, tensile stresses should not exceed tensile strength of the concrete. However, a certain number of stress excursions above the tensile strength is accepted for dynamic loadings.
The performance evaluation and the assessment of damage level is formulated based on magnitudes of Demand-Capacity Ratios (DCR), cumulative duration of stress excursions beyond the tensile strength of the RCC and spatial extent of overstressed regions
The acceptable level of damage on the basis of linear-elastic analysis is presented by a performance curve, as shown in figure below, taken from [6], page 4.4.

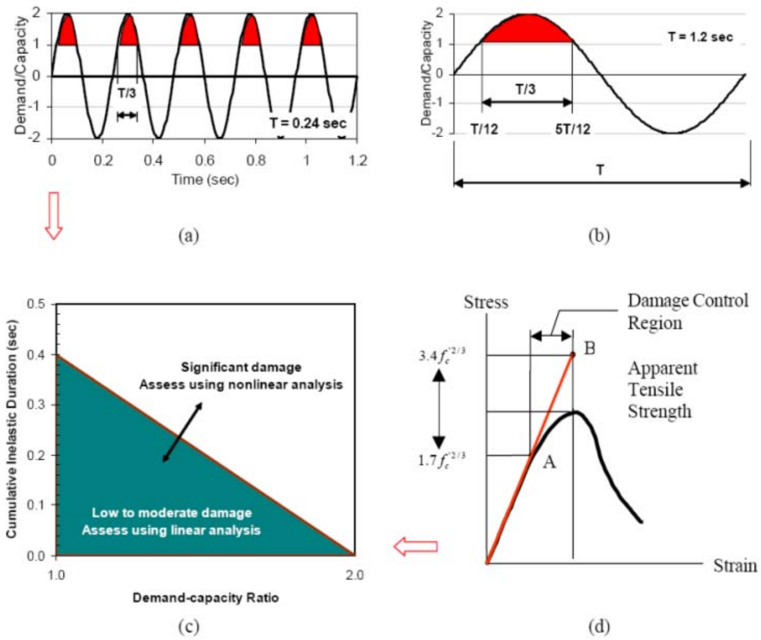


Fig. 11 – Basis for upper limit Demand-Capacity Ratio and Cumulative Inelastic Duration

The maximum permitted DCR for linear transient dynamic analysis of dams is 2. This corresponds to a stress demand twice the static tensile strength of the concrete. As illustrated in the stress-strain curve in figure above, the stress demand associated with a DCR of 2 corresponds to the so called "apparent" dynamic tensile strength of the concrete, used for evaluation of the results of linear dynamic analysis.

The dam response to an earthquake is considered to be within the linear-elastic range of behavior with no possibility of damage, if the computed stress demand-capacity ratios are less than or equal to 1.0. The dam would exhibit nonlinear response in the form of cracking of the concrete and/or opening of construction joints if the estimated stress demand-capacity ratios exceeds 1.0.

The level of nonlinear response or cracking considered produces low or moderate damage if the demand-capacity ratios are less than 2.0, damage is limited to 15 percent of the dam cross-sectional surface area and the cumulative duration of stress excursions beyond the tensile strength of the concrete falls below the performance curve given in the figure reported above.

Consideration should also be given to the relation between the fundamental period of the dam and peak of the earthquake response spectra. If lengthening of the periods of vibration due to nonlinear response behaviour causes the periods to move away from the peak of the spectra, then the nonlinear response would reduce seismic loads and improve the situation by reducing stresses below the values obtained from the linear time history analysis. When these performance conditions are not met, or met only marginally with the nonlinear response increasing the seismic demand, then a nonlinear time-history analysis might be required to estimate the damage more accurately.

2. Dam Features

The Grand Ethiopian Renaissance Dam (GERD) Project is located 500 km north west of the Ethiopian capital of Addis Abeba, in the Benishangul – Gumaz region, along the Blue Nile River.
The Ethiopian Electric Power company (EEP) is the employer, Salini-Impregilo SpA the EPC Contractor and Studio Pietrangeli Srl the designer.
The plant, with its 6’140 MW of installed power and 15.7 TWh of annual energy production, is one the most important projects in the Ethiopian Government’s commitment to meet the country’s present and future power requirements. The hydropower plant is currently under construction. When completed, GERD will be the largest plant in Africa.

The general layout of GER Main Dam is illustrated in the figure reported below. The key components of the project are:

- a Roller Compacted Concrete (RCC) Main Dam with a maximum height of 175 m and a total volume of RCC of about 10.2 million cubic meters;
- a Concrete Faced Rockfill (CFRD) Saddle Dam 60 m high and 5 km long, with an embankment volume of 17 million $m^{3;}$
- a system of three spillways safeguards the project against the Probable Maximum Flood (30’200 m^3/s peak and 18’000 m^3/s routed discharge);
- sixteen penstocks (8 m diameter), embedded in the dam body. Two penstocks at lower elevation are dedicated to early generation during reservoir impounding;
- two outdoor power houses located at the Main Dam toe on the right and left riverside housing ten Francis turbine units and six Francis turbine units respectively, with 400 MW each totalling 6’140 MW installed capacity;
- one 500 kV switchyard on right bank.

Fig. 2 – GERdp hydroelectric project, Main Dam general layout

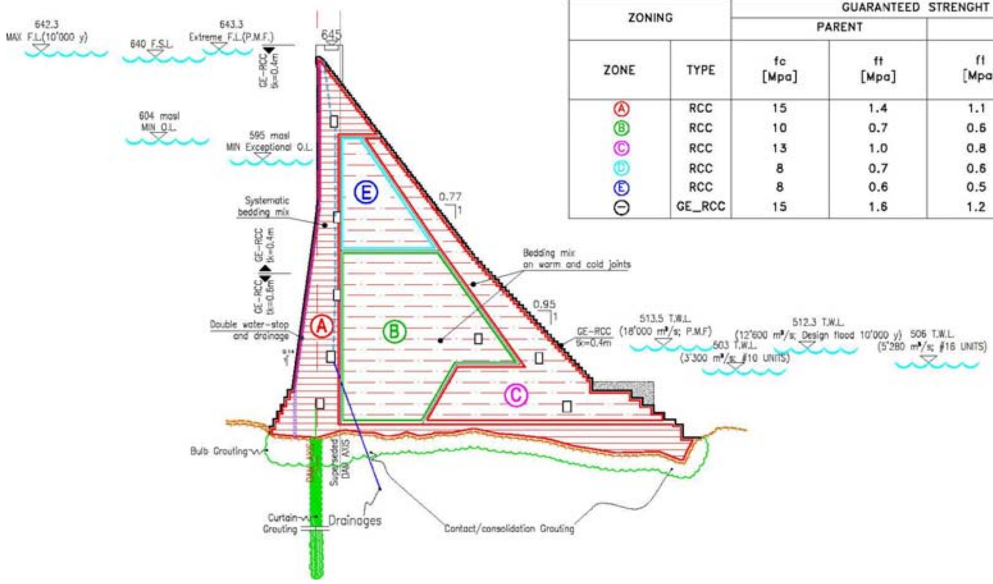
The Main Dam is a Roller Compacted Concrete gravity dam with a maximum height of 175 m and a length of about two km at crest elevation (645 m a.s.l.). Two typical sections are designed:

- Overflow Section (stepped spillway)
  The upstream face has a 0.14:1 (H:V) slope in the lower portion (below elev. 575 m a.s.l.) and vertical in the upper portion. The stepped downstream face has an average slope ranging from 0.77:1 to 0.95:1 (H:V)
- Non-Overflow Section
  The upstream face has a 0.10:1 (H:V) slope in the lower portion (below elev. 545 m a.s.l.) and vertical in the upper portion. The stepped downstream face has an average slope of 0.77:1 (H:V).

The dam has 85 monolith blocks separated by cutting joints into the freshly RCC after compaction. The vertical contraction joints are equipped in the upstream zone with double waterstops and control drainage. The contraction joint spacing along the dam axis varies from 18 to 27 m. The joints spacing is controlled by thermal issues and by the dimensions of the concrete structures of electro-mechanical equipment (penstocks, culverts and bottom outlets) crossing the dam body.

The dam is equipped with five main longitudinal galleries, every 30-40 m of height, located close to the upstream face and sized in order to efficiently carry out drainage and grouting works. Transversal (u/s-d/s) galleries are foreseen to allow the access from the downstream face, seepage water monitoring and discharge.
A wider and more detailed description of the dam, which would go beyond the purposes of the present article, can be read in [3].

Fig.3: GERDP Dam under construction



RCC MIXES DESIGN PARAMETERS						
ZONING		GUARANTEED STRENGHT VALUES at @365d				
		PARENT		LIFT JOINT		
ZONE	TYPE	fc [Mpa]	ft [Mpa]	ff [Mpa]	c [Mpa]	φ [°]
Ⓐ	RCC	15	1.4	1.1	1.0	45
Ⓑ	RCC	10	0.7	0.6	0.7	45
Ⓒ	RCC	13	1.0	0.8	0.8	45
Ⓓ	RCC	8	0.7	0.6	0.7	45
Ⓔ	RCC	8	0.6	0.5	0.7	45
⊖	GE_RCC	15	1.6	1.2	1.0	45

Fig.4 – GERD overflow section (geometry, mechanical characteristics zoning, extension of lift bedding mix).

3. Methodology

The present paragraph describes the FEM models, the design loads and criteria, the post processor adopted to perform the DCR-CID analyses of the dam.

3.1 FEM models

The bi-dimensional Finite Element Models used for the purposes of the time history analyses were based on the following assumptions:

- Dam and rock are modeled with 4 nodes quadrilateral Plate-shell elements;
- Both rock and concrete are assumed to be elastic and isotropic;
- The boundaries of the rock mesh are specified at an horizontal length of 4,0 times the dam height from upstream and downstream toe and the same dimension in the vertical direction.

The restraints imposed to the nodes at the limiting surfaces of the overall FEM model are the following:

- nodes at the base of the dam - fixed in all directions;
- nodes at the left and right edges of rock - fixed in horizontal (u/s to d/s) direction;
- all the other nodes – free.

The sketch below shows a typical FEM basic geometrical model adopted.

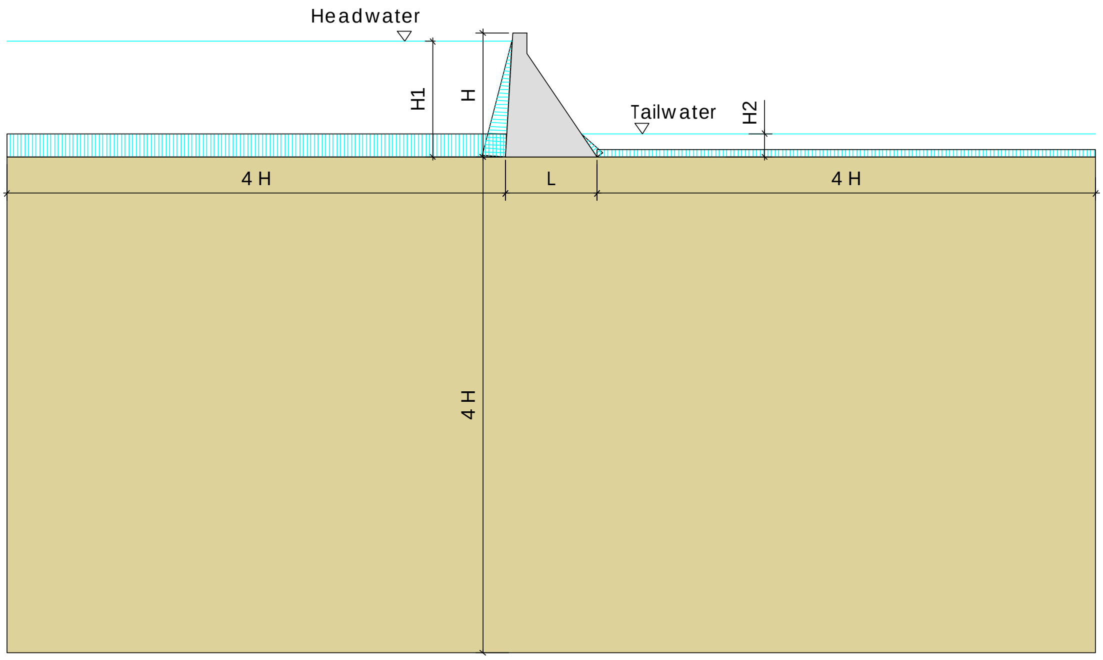


Fig. 5 – FEM geometrical model

The following figures represent the FEM model adopted for one of the most representative sections, which is the main overflow, together with mechanical properties of RCC in terms of Young Modulus.

The typical size of the quadrilateral elements are about:

- 1,5x1,5 m, in the dam body and in the rock near the dam foundation;
- 20x20 m, in the rock far from dam-rock contact.

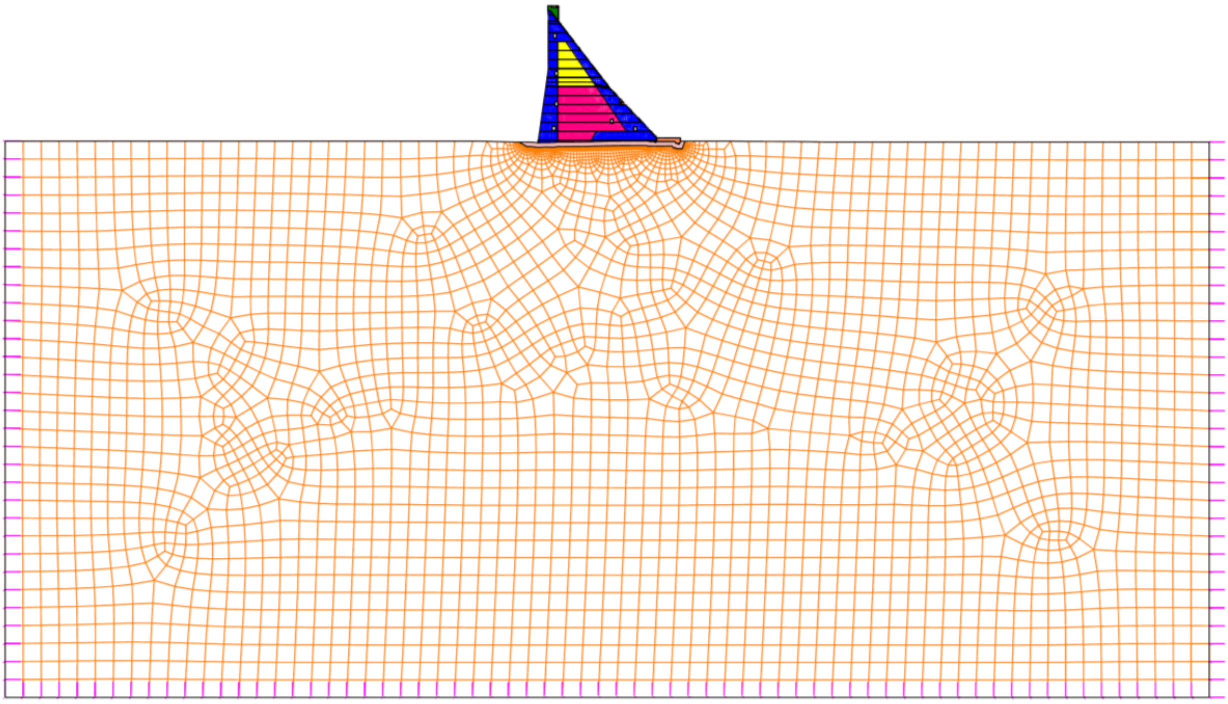


Fig. 6 – Main Overflow Section - FEM MODEL

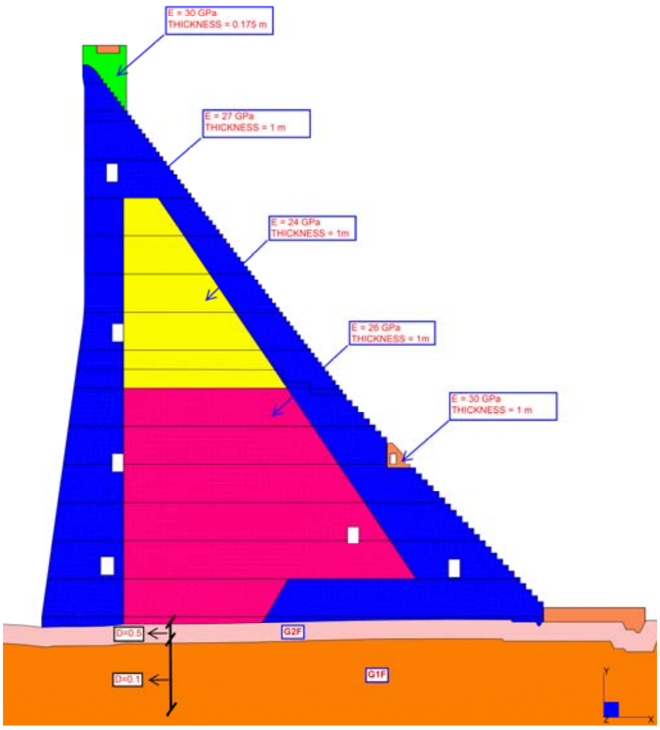
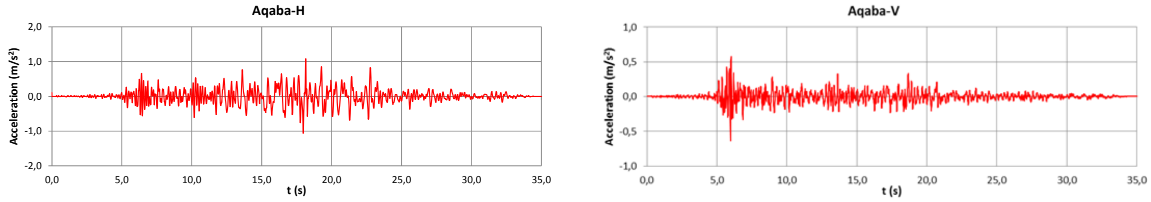


Fig. 7 – Main Overflow Section – FEM MODEL – detail of the dam

3.2 Loads and design criteria

The input accelerograms were taken from the Seismic Hazard Analysis which defined, for SEE, a set of six scaled natural accelerograms matching the design spectra, both for the horizontal and the vertical component.
The horizontal and vertical components of selected Time-Histories, used in the seismic analyses of dam sections, are reported in the following figures.



Fig, 8 – Time History of ground acceleration – Horizontal (left) and Vertical (right) component - Aqaba

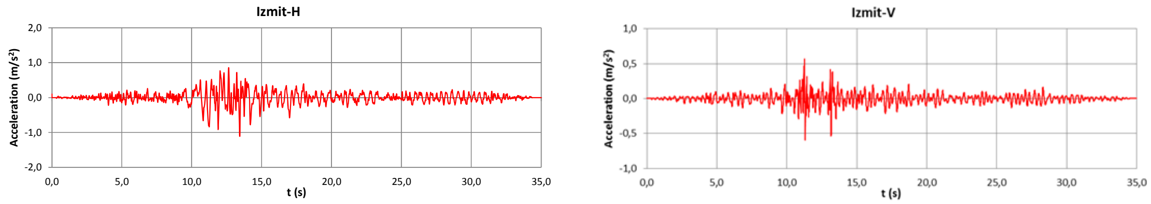


Fig. 9 – Time History of ground acceleration – Horizontal (left) and Vertical (right) component - Izmit

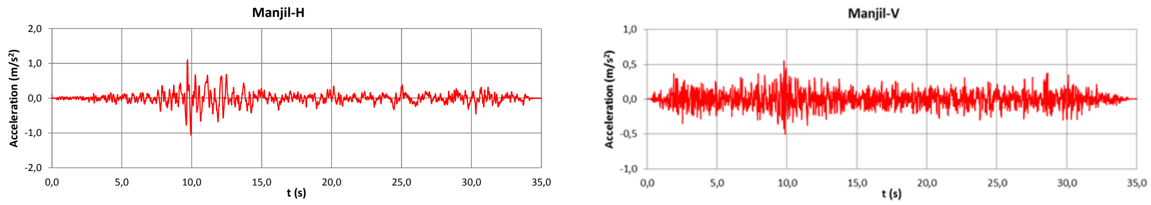


Fig. 10 – Time History of ground acceleration – Horizontal (left) and Vertical (right) component - Manjil

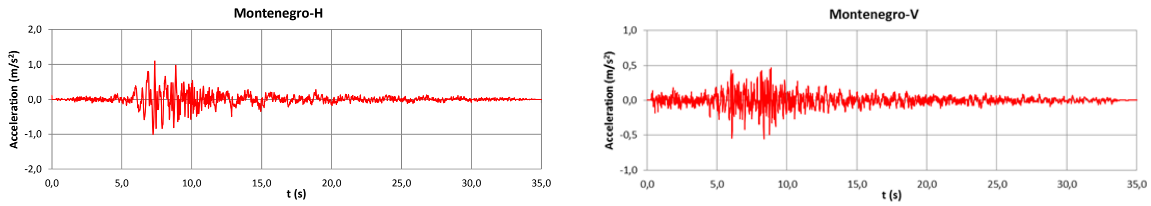


Fig. 11 – Time History of ground acceleration – Horizontal (left) and Vertical (right) component - Montenegro

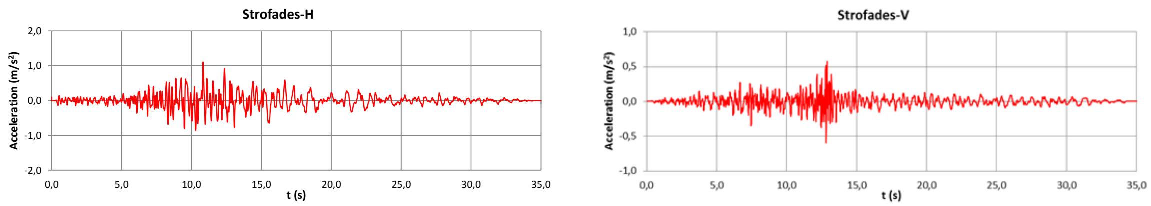


Fig. 12 – Time History of ground acceleration – Horizontal (left) and Vertical (right) component - Strofades

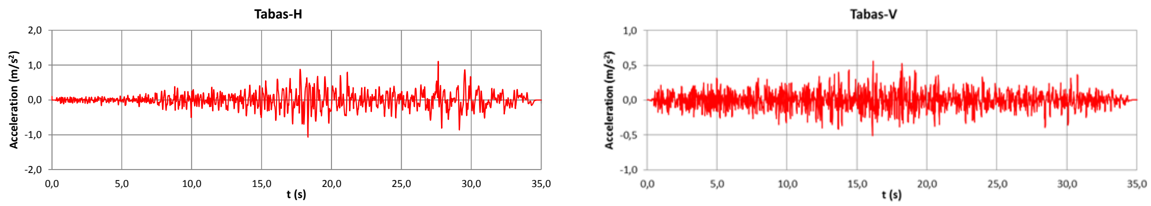


Fig. 13 – Time History of ground acceleration – Horizontal (left) and Vertical (right) component – Tabas

The figure below shows a comparison between the response spectra of the natural scaled accelerograms and the elastic one for SEE loads.
It can be noted that, in the range of interest, the response spectrum of the accelerograms is very close to the elastic one.

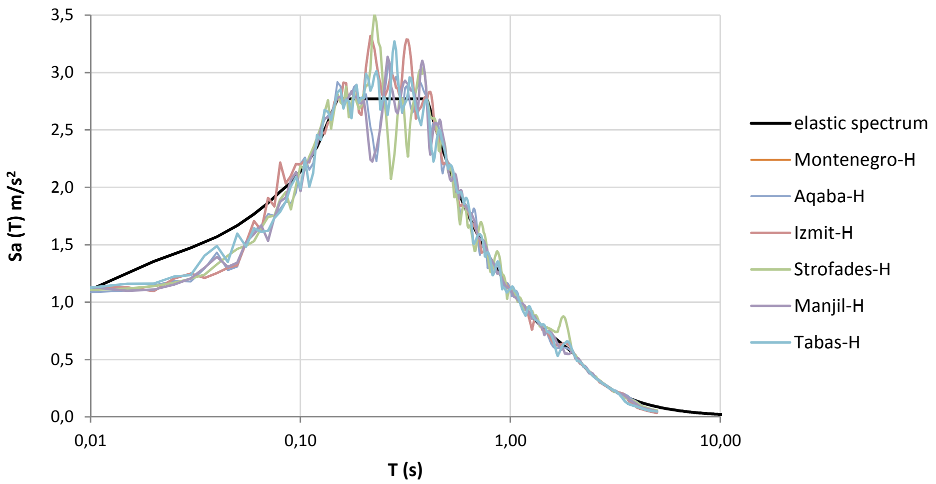


Fig. 14 – Elastic spectrum vs all earthquakes spectra – Horizontal component

As to design criteria, it is recalled that the stability of a gravity dam under seismic events can be assessed by a simplified linear procedure if the performance curve falls below the limit line reported in the figure below taken from [7], page 6-11.

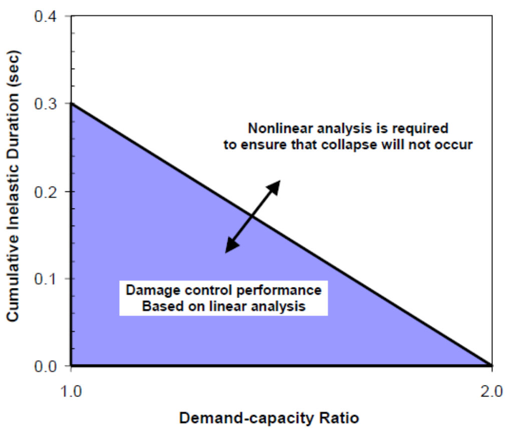


Fig.15 – Performance curve for concrete gravity dams [7]

Each section of the dam has been analyzed considering all the six earthquakes and the four load combinations H+V, H-V, -H+V, -H-V, in which H refers to the horizontal component of seism and V to the vertical one.

The most severe load combination was considered for each earthquake and then the average effects of the six earthquakes were taken into account to infer the demand curve, to be compared with the limit line and to decide whether stability was proved by the DCR-CID method or further Non Linear Analyses were necessary.

3.3 Post processor

In order to apply practically the rational method described theoretically in the introduction of the present article, a dedicated computation code has been developed, tested, validated and systematically adopted by the engineers of Studio Masciotta.
The computation code consists of a series of Excel Macros and Straus 7 API (Application Programming Interface) which have the purpose of extracting the results from FEM model and computing the Demand-Capacity Ratio and the Cumulative Inelastic Duration of selected control points within the dam body.

It has to be taken into account that, in order to study the behavior of a dam with a so important length (about 2 kilometers) and a consequent great variety of geometries and foundation characteristics, a series of **fifteen transversal sections** has been analyzed (about a section every 130 meters of length) by means of dedicated 2-D FEM models.

Every section has been analyzed at least considering **two** possible and alternative geometries, in order to identify the optimum one.

Within every transversal section of the dam, an average number of about **fifteen control points** has been fixed in order to inquire the dynamic behavior of the dam under seismic events.

Every transversal section has been analyzed considering **six** different earthquakes, as explained in the previous paragraph, considering the **four** possible combinations of signs of the horizontal and the vertical component of every seism.

Each adopted earthquake lasts 35 seconds, and in the linear time history analysis steps of integration have been set every 0.005 seconds, so having **seven thousand** steps of integration for each combination of earthquake.

The inquired points have been analyzed both in terms of vertical stresses (to be compared with lift joint tensile strength) and maximum principal stresses (to be compared with parent tensile strength), so having **two** relevant quantities to be examined in each control point

It is therefore easy to infer that the quantity of data to process in order to obtain manually the required graphs of DCR and CID for the inquired sections of the dam is given by the product: $15 \times 2 \times 15 \times 6 \times 4 \times 7000 \times 2 \approx 151$ millions of data.

Assuming that an engineer can process a datum every two seconds, if he worked without interruption for the whole working day (assumed to be of 8 hours), he would take 10500 days, which is **more than 28 years**, in order to produce the required result, moreover with the concrete possibility of introducing widespread human errors in the processed data, whose reliability would be strongly affected.

In the light of what above, the idea of developing a dedicated software was deemed not just a reasonable optimization of the work of the engineers, but rather an absolute necessity in order to comply with the times agreed between the Designer Studio Pietrangeli Srl and the EPC Contractor Salini Impregilo.

The post processing software is articulated in five sub-routines: Init, Eval DCR-CID, Graphs, Synth, Print.

The post processing software presupposes to have correctly performed a linear time history analysis of the sections of the dam, in accordance with [6], therefore all the result files are supposed to be available for the purposes of the current article.

Init is the interface with the FEM software Straus 7. In fact, it contains the calls to Straus 7 API. The user can choice if the API shall get either the vertical stresses or the maximum principal ones and shall select which plates he wants to investigate. Obviously, the engineering judgement is fundamental in this phase, in order to contain the size of data that the software shall process. The routine cycles on all the elements of the FEM model and extracts the time history of vertical/maximum principal stresses of the ones selected by the user, for all the saved time instants.

Eval DCR-CID is the core of the calculation process performed by the software. It considers the time history of stresses extracted during the phase Initialize (Demand) and it compares them, step by step, with the Capacity value introduced by the user. Then it evaluates the Cumulative Inelastic Duration (CID) for DCR values ranging from 1 to 2 (it is recalled that a DCR greater than 2 is not allowed).

Graphs uses the data computed by the sub-routine Eval DCR-CID to produce the graphs of DCR and CID, in order to compare them with the limit line prescribed by [6], figure 4-1 (c), and to establish whether stability can be assessed by the simplified Linear Analysis (Low to moderate damage) or it's necessary to perform a further Non Linear Analysis (Significant damage).

Synth is a routine responsible only for the chart sorting and formatting. It produces an Excel sheet for every selected element of the FEM model and puts the graphs relative to the element in the sheet itself; then it formats the charts in order to make them easy readable and ready to be printed and presented in a calculation Report.

Print gets the graphs produced by the routine Synth and produces a pdf file for every graph, containing the graph itself, ready to be assembled in the Annex of a Calculation Report of the Dam.

4. Results of DCR/CID analysis

The typical results of the DCR analysis performed using the software is reported here below, both for a control element for which the verification by means of linear analysis is satisfied and for an element in which the acceptance limit is exceeded.

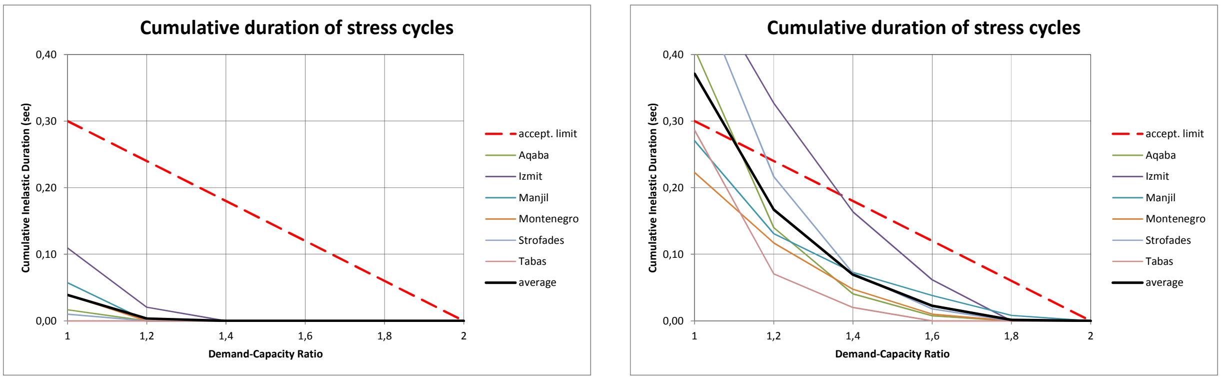


Fig.16 – Examples of an element fully verified according to DCR method (left) and of an element not verified (right)

It's important to premise that the process of optimization of the dam by means of linear time history procedure was carried out essentially during level 2 Design.

The dam had been already well dimensioned during basic and level 1 Design using simplified pseudo static methods (Seismic Coefficient Method, Equivalent Lateral Force Method) and modal analyses with Response Spectrum.

This involved that all the analyzed geometries and sections resulted generally verified and the linear time history procedure with DCR-CID method was used essentially with the aim of optimizing of the section themselves. More in detail:

- Some corners and singular points presented DCR values very close to the allowable limits and, in some cases, even above the limit line fixed by USACE codes to assess the stability of the dam by means of simplified linear procedure. The geometry was locally adjusted in order to achieve a better performance, for example by introducing in correspondence of the changes of u/s and d/s slope proper chamfers which greatly improved the behavior of those singular points under earthquake, allowing a better stress flow;

- The demand values of lift joint and parent tensile strength were optimized by using systematically the software and performing iterative analysis. For each dam section, and for all the inquired elevations, the value of DCR=1 (corresponding to the tensile strength of the material) was gradually decremented following an iterative process aimed at identifying the minimum values of tensile strength which allowed to assess the stability of the dam through DCR-CID procedure; consequently, maps of the minimum required tensile strength of the material were produced. This systematic procedure allowed to achieve demand values tipically 20% lower than the ones predicted during level 1 Design by means of Modal Analysis with Response Spectra.

Fifteen sections were systematically analyzed during Level Two Design adopting the simplified DCR approach and the relative calculation reports were produced. An approximate number of **9.000 DCR-CID synthesis graphs** was produced using the software described at paragraph 3.2.

It resulted that fourteen sections were fully verified and their stability under earthquake SEE was assessed through the linear time history analyses; besides, as said above, they were also optimized in terms of geometry and of tensile strength demand of the material.

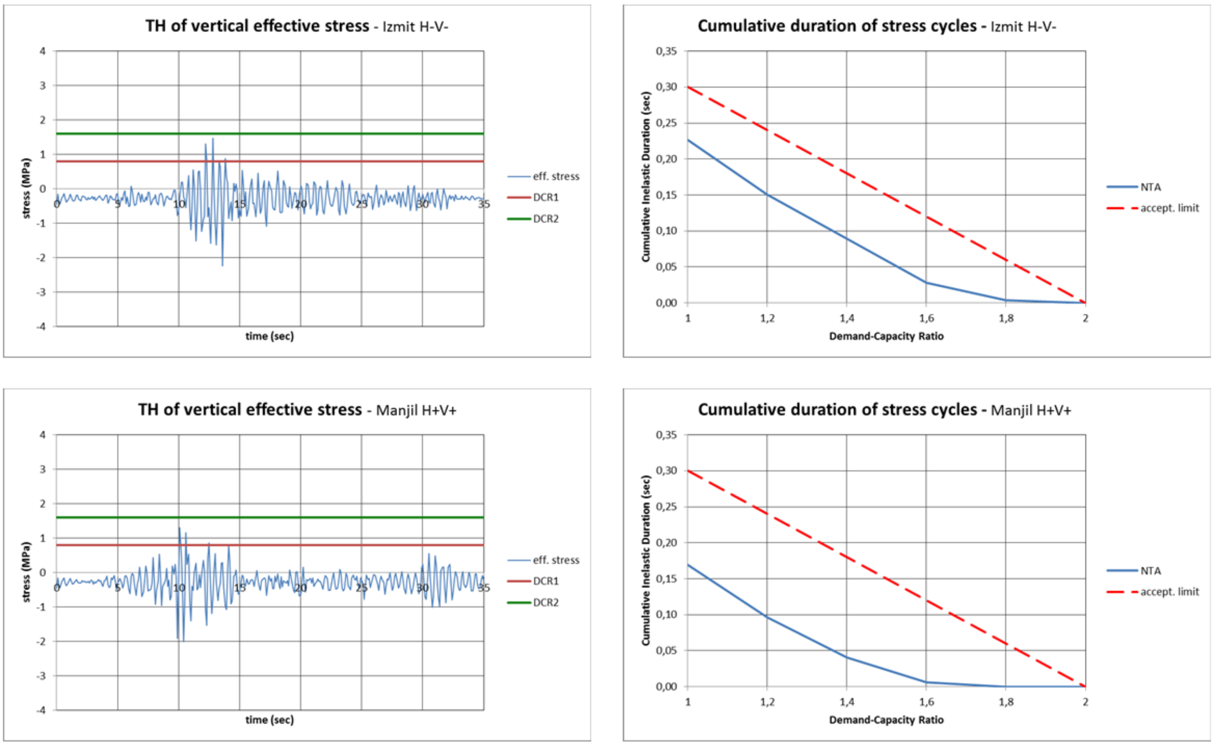


Fig. 17 – Examples of elements of sections fully verified through DCR method – Time history of stress (left) and DCR-CID graph (right) for two different earthquakes

Only the stability of the highest section of the dam, the one in correspondence of the Gorge, resulted to have some critical points in which the DCR values were exceeded adopting the tensile strength values fixed during Level One Design. For this singular section, the linear time history analysis represented all the same a useful tool to identify the critical zones in correspondence of which crack could be expected during seismic events. Further Non Linear Analyses were performed, assuming the potential crack surfaces identified by means of the linear time history analyses, and they led to assess the stability of the section confirming that permanent sliding displacements do not occur. These further analyses are not object of the present paper and they will not be dealt with.

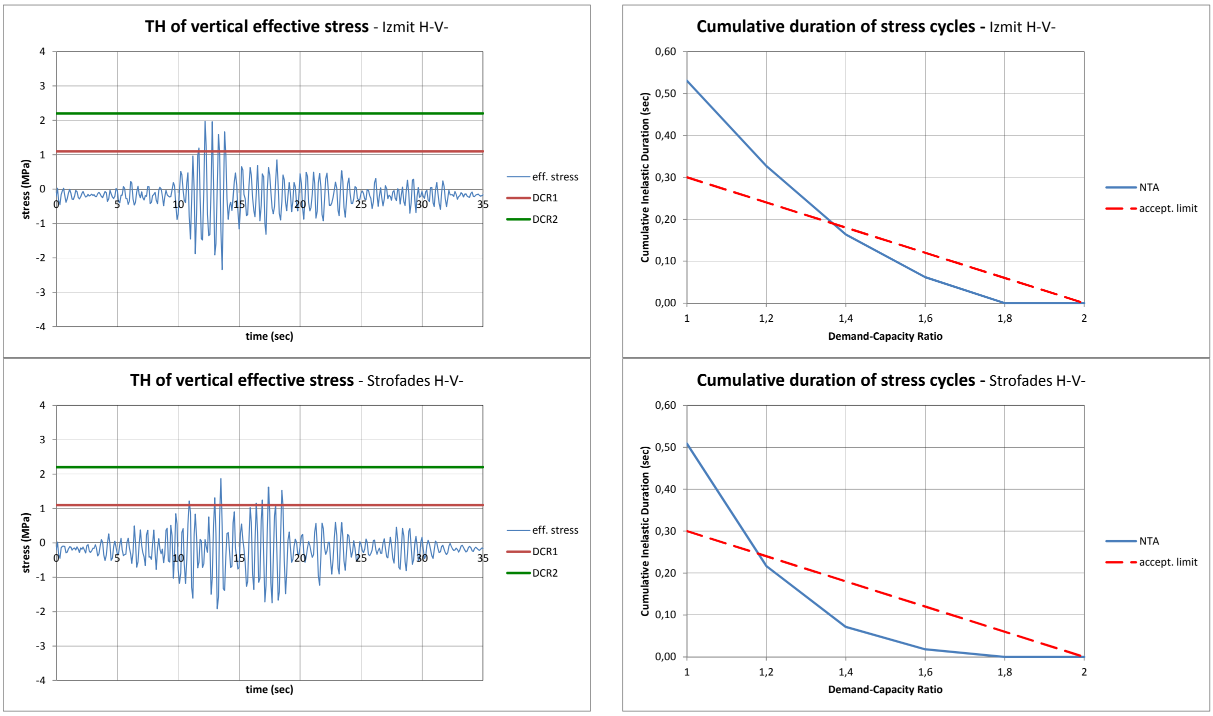


Fig. 18 – Examples of elements of sections not verified through DCR method – Time history of stress (left) and DCR-CID graph (right) for two different earthquakes

5. Conclusions

The paper presents a systematic and rational application of the most well-known, validated and widespread methodology to estimate the behavior of concrete structures under seismic loads, using linear time-history analysis.

This methodology is the Demand Capacity Ratio (DCR) approach proposed by USACE Code, EM 1110-2-6051.

A dedicated calculation code was written to automate the use of the method, allowing an enormous saving of time, reducing almost to zero the possibility of human errors in the output data and minimizing the number of Non Linear Analyses required to assess dam stability.

The developed software was systematically adopted to verify the stability under extreme (SEE) earthquake loads of the Grand Ethiopian Renaissance Dam which, once finished, will be the largest plant in Africa.

In spite of the huge dimensions of the dam and the enormous quantity of data to be processed, the use of the software allowed to complete the stability analyses under seismic loads of the dam in reasonable times and led to important marginal but significant optimization in the design of the dam, especially in terms of geometry details and of tensile strength demand.

The stability of all the transversal blocks of the dam could has been assessed by means of the simplified DCR approach. Only the highest section, which was the one in correspondence of the Gorge, required greater efforts since its stability could be assessed only by means of further and more time consuming Non Linear Analysis. However, even in this case, the preliminary analysis by means of DCR approach, represented a necessary and fundamental step in order to identify the surfaces most likely to crack under strong seismic events and to carry out the Non Linear Analyses in the light of this fundamental information

References

1. **Sonawane M.B., Dubey S.K., Deodhar S.V., .** "An Analitical Approach to demand-capacity method", International Journal of Advanced Technology in Civil Engineering, ISSN:2231-5721, Volume-2, Issue-1, 2013
2. **Yamaguchi Y., Hall R., Sasaki T., Matheu E., Kanenawa K., Chudgar A., Yule D.,** "Seismic Performance Evaluation of Concrete Gravity Dams ". 13th World Conference on Earthquake Engineering, Vancouver (Canada), 2004
3. **Pietrangeli G., Bezzi A., Rossini C., Masciotta A., D'Alberti D..** "Design of Grand Ethiopian Renaissance RCC Main Dam (H= 175 m) ", Hydropower & Dams, 2017
4. **Straus7**, "Theoretical Manual – Theoretical background to the straus7 finite element analysis system", September 2004
5. **US Army Corps of Engineers**, "Gravity dam design", EM 1110-2-2200, 1995
6. **US Army Corps of Engineers**, "Time-History Dynamic Analysis of Concrete Hydraulic Structures", EM 1110-2-6051, 2003
7. **US Army Corps of Engineers**, "Earthquake Design and Evaluation of Concrete Hydraulic Structures", EM 1110-2-6053, 2007
8. **ICOLD Bulletin 72**, "Selecting seismic parameters for large dams", 1989
9. **ICOLD Bulletin 148**, "Selecting seismic parameters for large dams", 2010 Revision
10. **Hatami K.,** "A Measure of Dynamic Response for Seismic Response Analysis of Concrete Dams," 6th U.S. National Conference on Earthquake Engineering, Seattle, WA, 1998.
11. **Hall R., Matheu E., Liu T.,** "Performance Evaluation of the Seismic Response of Concrete Gravity Dams," International Conference on Health Monitoring of Civil Infrastructure Systems, Chongqing, China, 1999.

The Authors

A. Masciotta obtained his degree in Civil Engineering from the University of Rome "La Sapienza".
He worked for fifteen years for Studio Pietrangeli as senior engineer on hydropower projects. He is the founder in 2006 of Studio Masciotta in Rome and is chief civil works designer for dams and hydropower projects. He actually collaborates with Studio Pietrangeli as structural independent expert.

A. Bezzi graduated with honors in civil and hydraulic engineering at the University of Rome "La Sapienza". Working with Studio Pietrangeli, he has acquired over 20 years of experience in the field of design and project management of large dam and hydropower projects. He is GERD Project Coordinator for Studio Pietrangeli.

C. Fontana graduated in civil engineering at the University of Rome "La Sapienza".
He is specialized in anti-seismic structures and collaborates at the University of Rome "La Sapienza" in the Structural Engineering and Geotechnical Department.
He has been a consultant for Studio Masciotta since 2012 as expert of application programming interface for structural verifications.

A. Fiorani graduated with honors in civil engineering at the University of Rome "Tor Vergata". He specialized in structures and since 2011 he has been working with Studio Pietrangeli; he has been deeply involved in the stability analyses of the large dams of Gibe III and GERDp and in the design of their appurtenant structures (spillways, concrete piers, bottom outlets, culverts, road and crane bridges).